Action Understanding via Mirror Neuron Systems: A Proposed Model for the Science and Treatment of Stuttering

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A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of the requirements of the Sally McDonnell Barksdale Honors College.

Oxford
April 2017

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ACKNOWLEDGEMETNS

First, I would like to thank Dr. Greg Snyder for his continuous support and mentorship, and offer a bigger thank you for his patience. He taught me how to focus on an end goal and, above all else, how to get the job done. This project would not have even started, yet alone come together, without him. I am truly thankful for his constant guidance, through all 25 drafts.

To my readers, Doug Odom, Dr. Tossi Ikuta and Dr. Erin Reynolds-Peacock, I would like to offer a sincere thank you for your time and your valued input.

Finally, I would like to thank the Honors College, the Department of Applied Sciences, and the Department of Communication Sciences and Disorders for sparking my interest in new subjects and nurturing my love for others. The exposure to the field through these departments was invaluable to my project and my future studies.

ABSTRACT

Persistent developmental stuttering is generally considered to be a speech disorder characterized by repetitions, prolongations and postural fixations, and is relatively resistant to therapy. While mainstream stuttering therapy continues to rely on behavioral speech targets, recent research suggests that mirror neuron systems can be activated to temporarily induce natural sounding fluent speech in those who stutter via exposure to second speech signals. Despite the prevalence of speech-motor based stuttering treatments, a unified account of how and why fluency is enhanced through endogenous methods remains elusive. The purpose of these two exploratory studies is to further test the validity of the mirror neuron systems, relative to stuttering, by examining the potential role of action understanding on fluency enhancement via (1) different levels of similarity between endogenous gestural priming and the production of targeted speech gestures and (2) producing and perceiving an initiating silent opening oral gesture

Study data support that endogenous gestural priming enhances fluency in those who stutter, with differential efficacy proportional to the similarity between gestural prime and targeted speech gesture. Additionally, data support that both the production and perception of initiatory gestural priming significantly enhance fluency. Coupled with existing research, these data suggest that fluency enhancement occurs through the activation of action understanding achieved through mirror neuron systems, allowing the speaker to bypass higher-order neural circuits associated with the etiology of stuttering. Data also reveal that overt stuttering behaviors are compensatory and corrective distal manifestations attempting to initiate the target speech gesture by circumventing an underlying higher-order block at the central level.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

PDS	Persistent Developmental Stuttering
SSS	Secondary Speech Signal
S	Self-generated
E	Externally-generated
G	Initiatory silent oral opening gesture
VF	Visual feedback
SG –VF	Self-generated initiatory silent oral opening gesture providing no visual feedback
EG +VF	Externally generated initiatory silent oral opening gesture providing visual feedback
SG+VF	Simultaneous production and perception of self-generated silent oral opening gesture providing visual feedback
SG + EG +VF	Simultaneous endogenous production and perception of exogenously generated silent oral opening gesture providing visual feedback

INTRODUCTION

Approximately 3 million people in the United States and about 67 million worldwide are affected by stuttering [1]. Persistent developmental stuttering (PDS) is a speech disorder that generally surfaces between two and four years of age [1], and is often behaviorally defined as three percent or more stuttered syllables during speech production [1, 2].

Overt stuttering moments are generally categorized into primary and secondary stuttering behaviors [3, 4, 5]. Primary behaviors manifest themselves as part- and whole-word repetitions, prolongations of sounds or syllables, and silent gestural fixations (e.g. “blocks” or prolonged pauses between sounds and words). Depending on the severity of the pathology, each stutter may last anywhere from less than one second to a full minute or beyond. Secondary behaviors include a vast array of initiatory or ancillary gestures, such as eye blinking, tonic or clonic tremors, or other bodily movements associated with syllable initiation that emerge as the struggle to speak intensifies [2, 3].

Several fluency-enhancing speaking conditions utilize either exogenous stimuli or endogenous changes in speech production, which are associated with gross changes in speech-related neurological activation patterns and are correlated with temporary fluency enhancement in those who stutter [1, 6, 7]. Research suggests that the most efficacious fluency enhancing strategy utilizes an external stimulus presenting a second speech signal (SSS). This SSS is a second concurrent and kinetically similar speech signal relative to the speaker's primary speech signal, and utilizes the strong link between gestural perception matching targeted gesture production, thereby enhancing fluent speech in those who stutter [1, 7]. These exogenous SSS are documented to enhance fluency in auditory, visual, and tactile sensory modalities [1]. Tangentially, endogenous fluency enhancing strategies include gross motor changes to speech production (such as singing, or speaking with a novel or foreign accent), as well as self-generated primes—such as opening and closing oral motor gestures prior to speech initiation [2, 8]. Data suggest that these fluency-enhancing conditions may act to inhibit the neural block associated with stuttering moments, thereby enhancing fluency in those who stutter [1, 8].

Research also suggests that the nature of gestural priming appear to display characteristics of action understanding, as the gestural primes that are most similar to the targeted action generally result in more efficient, effective and automatic initiation of the target gesture [9, 10]. Data reveal this to be true relative to fluency enhancement as well, as research documents the fluency enhancing effects of this "gestural tuning" between the perception and production of gestural primes with the targeted speech gestures, thereby approximating principles of action understanding [8]. Therefore, it has been suggested that enhanced fluency in those who stutter may follow the characteristics of action understanding achieved via mirror neurons [1].

Mirror Neurons were first discovered through research on monkeys in the 1990's when scientists discovered neurons firing equally when the monkeys witnessed an action as when the monkeys performed the same or similar action [11]. These mysterious single cells are located in the superior temporal sulcus (SPS), a long trench in the temporal lobe that separates the superior gyrus from the middle temporal gyrus, and are also believed to have strong implications in the production of speech and language [12]. Although the exact mechanism of these neurons is debated, it is generally agreed that a form of behavioral mimicry or matching is their most basic property. Mirror neurons allow motoric gestures, such as speech, to be immediately recognized. A representation of that action is then mapped for imitation, thus helping to bridge the gap between one agent and another through action understanding [9, 10, 11, 12].

Action understanding is the neural process through which an onlooker understands the behavioral intend of others, without preforming the behavior itself [10]. Research suggests that mirror neurons achieve action understanding by simulating the ‘goal’ of the action, as opposed to imitating the observed action in one’s own motor system [9,11,12]. Understanding, in this case, is achieved when an individual maps an observed action onto his or her own motor representation of that action, enabling him or her to immediately understand the goal [10, 12]. Action understanding, therefore, enables an onlooker to understand the goals of an action as an outcome to which one’s own goals can be directed without any higher order processing [11, 12]. This is pertinent to stuttering as a person who stutters can be provided with the framework for fluent speech gestures through the activation of these action understanding mirror neurons systems by a second speaker or stimulus [1, 8].

The idea that mirror neurons are primitive and do not use higher order processing is supported by research and is crucial in how mirror neurons assist with fluency. Mirror Neurons fire approximately 100 milliseconds after the onset of an action, suggesting that the imitation is spontaneous and reflexive [13]. Mirror neurons, therefore, are believed to be innate and require no training to develop. Although stuttering is also considered to be involuntary, the block appears to be with the distal origins in the central nervous system. This is applicable to stuttering because this primitive response is able to bypass or override the stuttering glitch, thus enhancing fluency.

Action understanding mirroring neurons can be used in therapy to help enhance fluency of those with a stutter through perception of a secondary speech signal (SSS), or the speech feedback of a second concurrent and kinetically similar speech signal. The SSS can be present as a visual, auditory or tactile sensory signal received synchronously or asynchronously relative to the primary spoken speech signal [1]. This signal activates the mirror neurons and allows the speaker to bypass their stuttering reflex and initiate more fluent speech.

The purpose of these two studies is to further test the feasibility of mirror neuron systems serving as a neurological framework relative to fluency enhancement in those who stutter. The first study measures the effects of endogenous gestural priming, utilizing different levels of "gestural tuning" (i.e. gestural similarity from priming to targeted action) as a means to approximate action understanding as a theoretical neural substrate of fluency enhancement. If fluency enhancement utilizes mirror neuron systems to achieve action understanding, it is predicted that the efficacy of fluency enhancement will be proportional to the differential effects of the proximity (or similarity) between gestural priming relative to the targeted speech gestures. Tangentially, the purpose of the second study is to test the effects of perception and/or production of an initiatory gesture (e.g. a silent opening oral gesture) on overt stuttering frequency. If the perception and/or production of a silent opening oral gesture utilizes action understanding achieved by the mirror neuron system, then the model predicts similar efficacy of fluency enhancement as a function of production and perception.

METHODS

Participants & Study Design

Eight adults with PDS (seven males and one female) participated in this research. Given that stuttering behavior is typically defined as three percent or more stuttered syllables (i.e. whole-word and part-word repetitions, prolongations, or inaudible postural fixations) during speech production [1, 2], a three percent stuttering frequency in a controlled speaking environment served as an inclusion criterion [1, 14, 15, 16]. Participants were all right-hand-dominant, native English speakers who reported normal or corrected vision, and no other diagnosed speech, attention or language disorders. All participants reported a minimum of a high school education, and read, acknowledged understanding, and signed an informed consent form prior to participation in these studies.

Experiment 1

Protocol

In the control and experimental speaking conditions, participants were asked to read passages from a junior high school science textbook, all of which have been used in previous research [1, 15, 16]. Each passage, consisting of ~300 syllables, was divided into 5 to 7 word phrases and was printed on large double-sided cue cards [1, 15, 16,]. For all speaking conditions, each participant was seated at a table (approximately 75 cm in height), and was then asked to read aloud from the phrases printed on the cue cards.

The following procedure was used in all speaking conditions in order to help control potential confounding variables [1, 2]. Demonstrations and practice trials were provided for every speaking condition until participants reported feeling comfortable with each speaking task. Participants were advised to speak at a normal rate and not to use any previously learned speech techniques that may help alter, control, or reduce stuttering behaviors [1, 15]. Conditions and reading passages were balanced using a Latin Square.

Control and Experiment Speaking Conditions

Each participant completed four speaking conditions that utilized different levels of endogenous gestural priming, approximating different levels of action understanding, which paired with the initiation of each initial speech gesture from every phrase spoken by the participant.

A no syllabic gestural priming speaking condition served as the control condition. A second speaking condition consisted of participants lightly striking the table with their right hand to initiate speech. This hand movement was approximately 25 centimeters from above the table surface; hand contact with the table served to initiate speech production.

A third speaking condition tested fluency enhancement through the use of a self-generated tongue-click produced by placing the tongue behind the front teeth, and pulling the tongue back, thereby creating suction and a clicking sound. This condition allowed participants to initiate a tongue clicking gesture without jaw movement.

During the fourth speaking condition, the participant produced a silent oral opening frame [15] as a means to initiate speech production; for the purposes of this study, a silent oral opening frame is defined as a silent opening mouth gesture as a means to initiate speech production. In all experimental speaking conditions, the different levels of action understanding gestural priming immediately preceded, and therefore initiated, speech production.

Data Collection and Reliability Analysis

All conditions were video recorded using a Sony Hi-8mm video camera (model #CCD-TRV75), and a lapel microphone (Radio Shack, model #33-3003) attached at ~0˚ to 180˚ altitude and no more than 15 cm from their mouth. Moments of overt stuttering were operationally defined as whole- and part- word repetitions, prolongations, or inaudible postural fixations [2]. Stuttering syllables were counted from the first 300 syllables of each speaking condition. Intrajudge syllable-by-syllable agreement, as indexed by Cohen's *kappa* [17], was 0.93. A trained research assistant independently analyzed these data, revealed an interjudge syllable-by-syllable agreement of 0.85, suggesting an excellent agreement beyond chance [18].

Experiment 2

Protocol

In the control and four experimental speaking conditions, participants were asked to read passages from a junior high school science textbook, all of which have been used in previous research [7, 14, 15]. Each passage, consisting of approximately 300 syllables, was divided into 5 to 7 word phrases and was printed on large double-sided cue cards [1, 14, 15]. For all speaking conditions, each participant sat at a table (approximately 75 cm in height), and was asked to read each phrase aloud. Participants were advised to speak at a normal rate and not to use any previously learned speech techniques that may help alter, control, or reduce stuttering behaviors [1, 15]. Speaking conditions and reading passages were balanced using a Latin Square.

Control and Experiment Speaking Conditions

Each participant completed a control speaking condition and four experimental speaking conditions. All included a silent oral opening gesture immediately preceding speech production. For the purposes of this study, a silent opening oral gesture was defined as a silent opening mouth gesture as a means to initiate speech production. The silent oral opening gesture (G) provided the core behavioral gesture in which to test the mirror neuron system hypothesis by comparing fluency enhancement resulting from either: (a) self-generated (S) initiatory silent oral opening gesture (G) providing no visual feedback (SG -VF); (b) externally-generated (E) initiatory silent oral opening gesture providing visual feedback (EG +VF); (c) simultaneous production and perception of self-generated silent oral opening gesture providing visual feedback (SG +VF); and (d) simultaneous endogenous production and perception of exogenously generated silent oral opening gesture providing visual feedback (SG + EG +VF). These four experimental conditions approximated different levels of action understanding when paired with the initiation of each initial speech gesture at the beginning of every phrase spoken by the participant.

For the control speaking condition, participants were instructed to read each phrase aloud without the use of a syllabic gestural prime. During the first experimental speaking condition, the participant produced a self-generated initiatory silent oral opening frame (SG -VF) as a means to initiate speech production.

A second experimental speaking condition consisted of participants simultaneously producing a self-generated initiatory silent open oral frame and receiving visual feedback from this gesture (SG +VF). This was achieved through the use of an AudiSee (Audisoft Technologies, model #HD-01A-0301-024), which is a head mounted video camera system, providing participants with a 14 centimeter visual display (measured diagonally) focusing on their lips, mouth, and jaw. The visual display was approximately 40 centimeters from the participant at his or her eye level, and this visual feedback served to initiate speech production.

Another experimental speaking condition was an externally generated initiatory silent open oral frame gesture with visual feedback (EG +VF). The experimenter wore the AudiSee device and provided the study participant with a silent oral opening frame visual prime, which was used to initiate speech.

In the final experimental condition, the experimenter again wore the AudiSee device while providing the participant with a visual feedback of a silent oral opening frame. When the participant began to see oral movement on the visual display, they were instructed to produce a silent oral opening frame of their own before starting speech. This final condition was the co-occurrence of a self-generated initiator silent speech gesture with the visual perception of an externally generated initiatory silent open oral gesture (SG + EG +VF). This combination of self-generated initiatory speech with externally generated feedback closely resembles a choral silent gesture. In all experimental speaking conditions, the different levels of action understanding gestural priming immediately preceded, and therefore initiated, speech production.

Data Collection and Reliability Analysis

All conditions were video recorded using a Sony Hi-8mm video camera (model #CCD-TRV75), and a lapel microphone (Radio Shack, model #33-3003) attached at ~0˚ to 180˚ altitude and no more than 15 cm from their mouth. Stuttering syllables were counted from the first 300 syllables of each speaking condition. Moments of overt stuttering were operationally defined as whole- and part- word repetitions, prolongations, or inaudible postural fixations [2, 7].

RESULTS

Experiment 1

The distribution of stuttering frequency as a function of action understanding gestural priming speaking condition is presented in Figure 1.

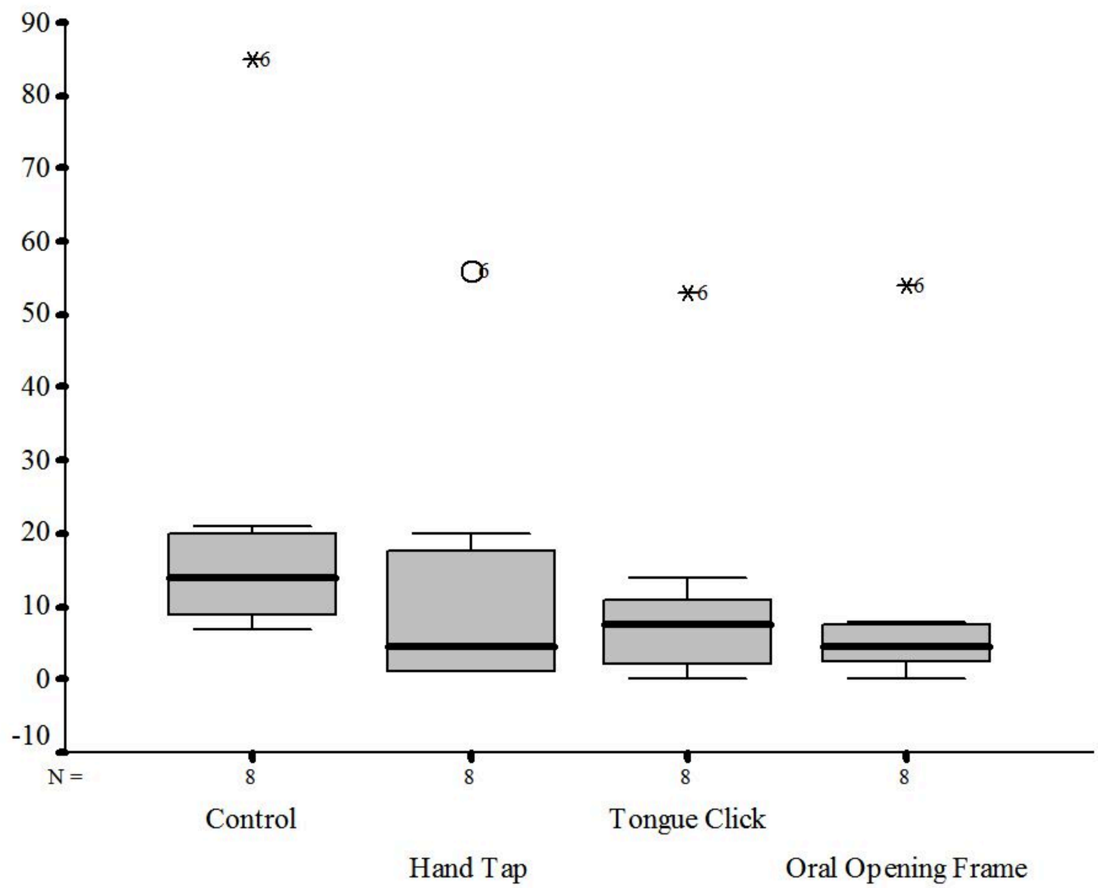

Figure 1. Minimum/maximum, inter-quartile range, and median values for the control, Hand Tap, Tongue Click, and Oral Opening Frame syllabic gestural priming speaking conditions. Note that "participant 6" is represented as a statistical outlier as a result of

differential levels of stuttering severity; however, the same pattern of fluency enhancement was produced by all participants.

The mean values of stuttering frequency were 22.25 stuttered syllables (SE = 9.141) for the control speaking condition, 12.88 stuttered syllables (SE = 6.65) for the initiatory hand movement speaking condition, 11.75 stuttered syllables (SE = 6.11) for the initiatory tongue-click speaking condition, and 10.36 stuttered syllables (SE = 6.31) for the initiatory oral opening frame speaking condition.

As shown in Figure 1, there was approximately 42% reduction of mean stuttered syllables with the initiatory hand movement speaking condition, 47% reduction occurred with the initiatory tongue-click speaking condition, and a 53% reduction occurred with the initiatory oral opening frame speaking condition. Because of the variance of overt stuttering severity within the small sample used in this study, a square root transformation was performed on the data before analysis, resulting in a more symmetrical and normalized distribution [1, 17]. Using these transformed data, a one factor repeated measure analysis of variance (ANOVA) revealed a main effect of gestural priming on stuttering frequency [$F(3,21) = 8.355$, Greenhouse-Geisser $p = .004$, $\eta^2 = .544$]. Post hoc comparisons, using the Bonferroni correction, reveal a statistically significant relationship between the control and the oral opening frame speaking condition ($p = 0.024$), reflecting the significant reduction in stuttering frequency and variance of stuttering moments between speaking conditions. Relationships between the control and the hand-tap ($p=0.178$), as well as tongue-click speaking conditions ($p=0.075$), were also revealed to be not statistically significant.

Experiment 2

The distribution of stuttering frequency as a function of action understanding gestural priming speaking condition is presented in Figure 2.

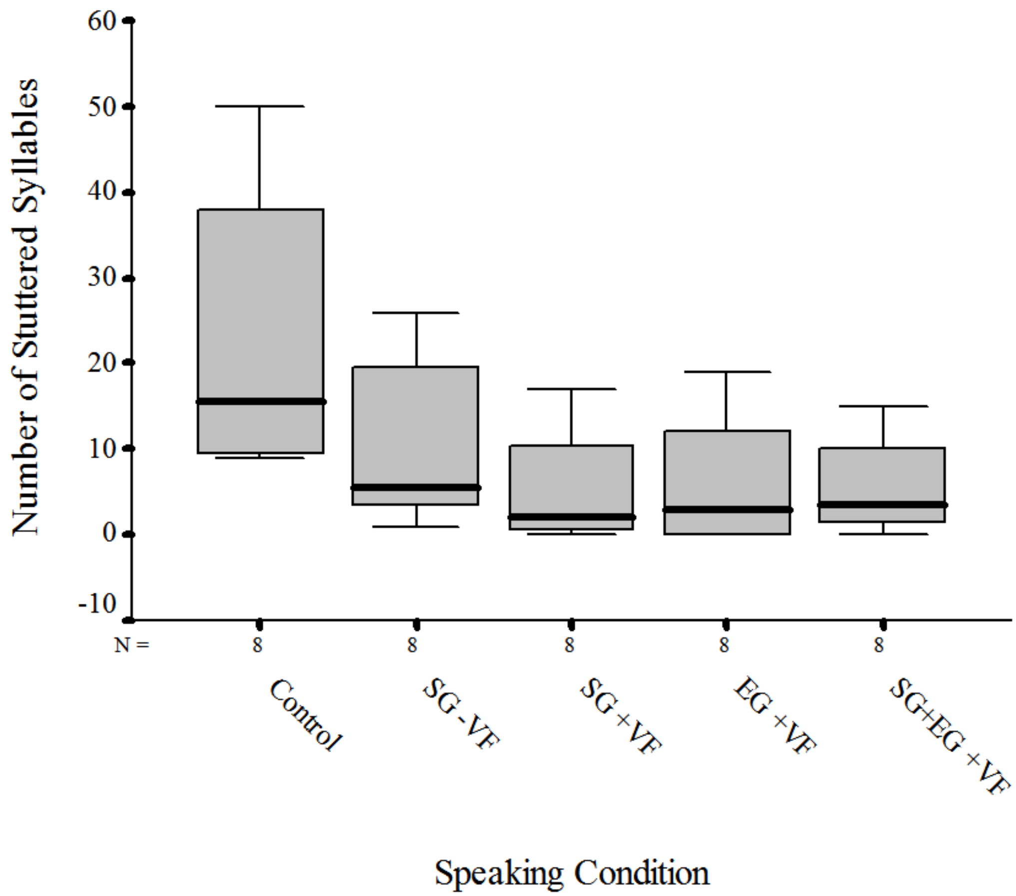

Figure 2: Minimum/maximum, inter-quartile, and median values for the Control Speaking Condition (Control), Self-Generated Prime without Visual Feedback (SG –VF), Self-Generated Prime with Visual Feedback (SG +VF), Externally-Generated Prime with Visual Feedback (EG +VF), and Self-Generated and Externally-Generated Prime with Visual Feedback (SG+EG +VF).

The mean value of stuttering frequency was 23.13 stuttered syllables (SE = 6.058) for the control speaking condition. The mean value for the production of the SG -VF was 10.50 stuttered syllables (SE = 3.417), approximately a 55% reduction of stuttered syllables. The perception of SG +VF had a mean stuttering frequency of 5.38 stuttered syllables (SE = 2.42), representing a 77% reduction of stuttered syllables. The EG +VF had a mean stuttering frequency of 6.13 stuttering syllables (SE = 2.682), approximately a 73% reduction of stuttered syllables. Finally, for SG + EG +VF the mean value of stuttering frequencies was 5.63 stuttered syllables (SE = 1.981), approximately a 76% reduction of stuttered syllables.

Due to the variance of overt stuttering severity within the small sample used in this study, a square root transformation was performed on the data before analysis, resulting in a more symmetrical and normalized distribution [1, 19]. Using these transformed data, a one factor repeated measure analysis of variance (ANOVA) revealed a main effect of gestural priming on stuttering frequency [$F(4,28) = 11.890$, Greenhouse-Geisser $p = .004$, $\eta^2 = .629$]. Bonferroni post hoc comparisons reveal a statistically significant difference between the control and SG -VF, SG +VF, SG+EG +VF, experimental speaking conditions ($p=0.000$, $p=0.12$, and $p=0.14$, respectively).

Intrajudge and interjudge reliability compared their analysis of 10% of the speech samples, chosen at random, with the original analysis of the data. A trained research assistant and the principal investigator both recalculated this 10% of the speech sample, chosen at random (as described in previous research) [19], and found interjudge syllable-by-syllable agreement was 0.89, as indexed by Cohen's *kappa,* [17]. Kappa values exceeding 0.75 suggest an excellent agreement beyond chance [19].

DISCUSSION

While existing data support the activation of a mirror neuron system as a means to enhance fluency in those who stutter [1, 16], data from these two studies reveal a relationship between stuttering amelioration as a function of action understanding gestural priming achieved through mirror neurons. In particular, post-hoc analyses of study 1 reveals an observable trending relationship between the similarity of endogenous gestural priming and efficacy of fluency enhancement, resulting in a statistically significant relationship between the control and the endogenous prime most similar to speech production. Consequently, the distributions of these data (as seen in Figures 1 & 2) are interpreted to potentially support the application of action understanding relative to the study of fluency enhancement in the speech of those who stutter, as the pattern of fluency enhancement reflects the similarity of the endogenous gestural prime and the target (speech) gesture. Stated succinctly, these data suggest that an endogenous gestural prime is most effective when it is most similar to its speech target—which is exactly what action understanding mirror neuron systems would predict.

Existing literature supports the application of a mirror neuron system relative to fluency enhancement via an exogenous SSS in those who stutter [1], with current data from this study suggesting that a mirror neuron system may employ action understanding as a means to account for the efficacy of stuttering amelioration. This finding is predicted by previous research in different animals, suggesting that action understanding via a mirror neuron system does not necessarily require behavioral mimicry [11, 12, 20]. The execution of both similar and even dissimilar endogenous motor programs can be linked with the intent or consequence of the target action, as opposed to the specific target action itself [11, 12, 20]. Moreover, the literature does suggest that the closer the gestural prime matches its gestural target (in either endogenous or exogenous forms), the deeper the action understanding [9, 10]. This has been demonstrated within stuttering research, in that while fluency can be enhanced with dissimilar gestural priming [9, 10, 11, 12, 20], the most efficacious and automated fluency enhancement occurs when the speech priming is closest to the actual motor-speech target [2, 9, 10].

Furthermore, data from study 2 confirms that the perception and production of initiatory gestures are not significantly different relative to efficacy of fluency enhancement. However, these data parallel previous findings in that the combination of self- and externally-generated initiatory gestures trends toward significantly more efficacious fluency enhancement relative to either production or perception alone [1]. These data, although utilizing oral gesturing rather than manual gesturing, are congruent with previous manual gesturing data in that both the production and perception of silent initiatory gestures significantly enhance fluency [1, 16, 21].

While these data continue to support the theoretical model for the enhancement of fluency via activation of action understand mirror neuron systems, little research has been committed to determine the role of action understanding within the enhancement of fluency in those who stutter. However, existing literature and data suggest that activation of mirror neuron systems may bypass specific neural circuits associated with the core etiology of stuttering, including the neural networks associated with speech and language processes [1, 4, 13, 16]. This applies to stuttering in that the primitive response of mirror neuron systems may enable the person who stutters to fluently initiate speech-motor gestures via a primitive lower order network, thus bypassing the higher order linguistic networks where the neural circuitry associated with stuttering is speculated to [1, 13, 16].

When coupled with existing research, these data support the supposition that stuttering behaviors may not accurately represent the pathology of stuttering itself, but rather that stuttering behaviors are in and of themselves the distal manifestations attempting to correct or compensate for the pathology occurring at central levels [1, 6]. This interpretation has been previously cited [1, 16, 22], with data suggesting that stuttering behaviors may be a form of endogenous gestural priming that the body is producing, thereby activating lower order primitive neural networks as an attempt to bypass the processing errors associated with stuttering and thus compensate for the pathology occurring at a central level [1, 16, 22]. Stated differently, the act of stuttering may be a natural compensatory reaction to bypass a block in higher order linguistic-motor processing via a primitive lower order network. Accordingly, the activation of action understanding mirror neuron systems can account for the nature of primary stuttering behaviors, which are the most common form of stuttering behaviors, and are also most similar to speech itself [1, 13, 16, 22]. This provides a novel insight into the role of stuttering behaviors themselves and supports that there is a genetic neural substrate associated with stuttering.

The perspective suggesting that the nature of stuttering behaviors serve as endogenous gestural primes via mirror neuron systems was unexpectedly and anecdotally reported by a number of research participants. Specifically, multiple study participants reported that the silent oral opening frame speaking condition was nearly indistinguishable from an act of stuttering itself. Even more, three participants revealed that the silent oral opening frame preformed in Study 1 was very similar, if not identical, to an uncontrolled stuttering behavior with which they had struggled in the past, and was subsequently targeted and addressed in stuttering therapy. Moreover, two participants reported that this study had reactivated these stuttering behaviors, which would have to be re-addressed in subsequent treatment. While this consequence for some study participants was certainly unintentional, these personal accounts of reactivated uncontrolled stuttering habits may support the notion that stuttering behaviors, in and of themselves, may be compensatory and corrective in nature, and appear to be modeled by action understanding.

While statistically significant, the amount of fluency enhancement provided by endogenous gestural priming strategies utilized in experiment 1 appears to be lower than that of other fluency enhancing strategies, particularly those employing exogenous SSS [1, 7, 23, 24]. This differentiation in performance between exogenous and endogenous fluency enhancing strategies was expected and can be accounted with the existing data documenting that voiceless (i.e., non-phonated) gestures do not enhance fluency as efficiently as voiced gestures [25] and with data suggesting that gestural primes work more effectively when they are perceived as exogenous stimuli, as opposed to self-generated and endogenous [1, 16, 26]. Additionally, Study 1 measured the effects of a singular gestural prime initiating an entire 5- to 7-word phrase, as opposed to a continuous SSS providing gestural primes initiating speech on a gesture-by-gesture basis. As such, it is expected and well documented that exogenous, multi-sensory, synchronous or asynchronous continuous SSS provide the most efficient fluency enhancement in those who stutter [1, 11].

In conclusion, both Study 1 and Study 2 support the use of the mirror neuron systems hypothesis as a theoretical model for the study of fluency enhancement in those who stutter. In addition, the nature of fluency enhancement via endogenous gestural priming appears to be in line with action understanding in relation to the goal of an action through the use of mirror neuron systems. As a result, data such as these lead to the supposition that stuttering behaviors may not be central to the disorder, as universally considered. Rather, the etiology of stuttering may be best conceived as a central disorder of higher order speech and language processing resulting from a genetic and neurological origin and that results in failures of cognitive initiation of linguistic motor plans. In compensation to these failures to initiate speech gestures, behavioral corrective responses, employing the use of action understanding achieved through mirror neuron systems, are manifested in the way of overt stuttering behaviors [1, 27, 28].

Future Research and Clinical Application

This novel view delineating the central pathology (i.e., higher order genetic/neurological) from compensatory stuttering (i.e., primary and secondary stuttering behaviors) is crucial to the development of the science of stuttering. Due to: (a) the compensatory nature of stuttering behaviors, (b) the genetic and neurological substrate relative to the core pathology of the disorder, and (c) data such as these which link perception and production (and thereby the mirror neuron systems hypothesis) relative to robust fluency enhancement, the treatment of stuttering ought likewise to evolve and adapt to reflect these developments in the science of stuttering. Treatments need to target the neural pathology or, at the very least, work with the neural and behavioral compensations (i.e., primary stuttering behaviors), as opposed to trying to suppress them. Additionally, future research in new treatment alternatives that integrate behavioral, prosthetic and pharmaceutical options is warranted, as they may better address the underlying core pathology of the disorder and help optimize lower order activations or other behavioral compensations via multi-sensory initiatory priming via production (volitional stuttering) or perception (prosthetic speech feedback) of a SSS.

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